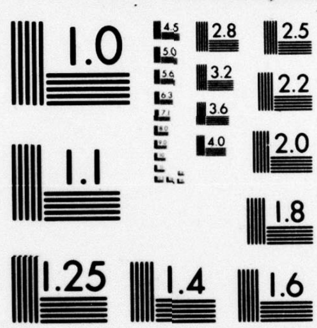
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SURFACE POLARITONS IN A DEGENERATE SEMICONDUCTOR WITH A SURFACE DEPLETION LAYER: HYDRODYNAMICAL MODEL*

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Surface polariton modes are investigated theoretically for a slab of one semiconductor on a semi-infinite substrate of a second semiconductor. Specific calculations are carried out for a slab of intrinsic GaAs on degenerate n-Ge. The case of a slab of degenerate n-Ge on intrinsic GaAs is also investigated.

1. Introduction

The development of attenuated total reflection[1] (ATR) has provided a valuable experimental tool for studying the properties of surface polaritons. Of particular interest are semiconductors in which one can have surface polaritons associated with both free carriers and optical phonons.

In this paper we present the results of surface polariton dispersion curve calculations for a slab of intrinsic GaAs on degenerate n-Ge and for a slab of degenerate n-Ge on intrinsic GaAs. A hydrodynamical model including non-local effects is employed[2].

2. Theory

First, we consider the elements of the non-local dielectric tensor. We start from the hydrodynamical equations of motion

$$m^* n(\dot{\vec{v}} + \vec{v} \cdot \nabla\vec{v}) = -ne\vec{E} - \nabla P \quad (1)$$

and the equation of continuity

$$\dot{n} + \nabla \cdot (n\vec{v}) = 0 \quad (2)$$

where the electron density n and velocity $\vec{v}$ are functions of position and time, m^* is the effective mass, $\vec{E}$ is the electric field, P is the electron pressure, and a dot over a symbol indicates a time derivative. Let the deviations of n and P from their uniform equilibrium values n_o and P_o be n_1 and P_1, respectively. For a degenerate electron gas we can take

$$\nabla P_1 = m^* \beta^2 \nabla n_1 \quad (3)$$

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and $$\beta^2 = v_F^2/3 \qquad (4)$$
where v_F is the Fermi velocity. Keeping only terms linear in the perturbed quantities and setting
$$(n_1,\vec{v},\vec{E}) = (\bar{n}_1,\bar{\vec{v}},\bar{\vec{E}})e^{i\omega t-i\vec{q}\cdot\vec{r}} \qquad (5)$$
we obtain the following expressions for the current density $\vec{j}$ and perturbed electron density n_1:
$$\vec{j} = (n_o e^2/im^*\omega)\vec{E} - (e\beta^2/\omega)\vec{q}\, n_1 \qquad (6)$$
$$n_1 = -(1/e\omega)\vec{q}\cdot\vec{j} \qquad (7)$$
By eliminating n_1, we can calculate the conductivity tensor and thence the dielectric tensor. We shall not present the detailed results for the latter, but merely state that certain elements are functions of the wave vector $\vec{q}$ as a result of the non-locality introduced by the pressure gradient term in Eq. (1).

Let us now consider the solution of Maxwell's equations for an intrinsic GaAs slab of thickness d sandwiched between vacuum ($z<-d$) and n-Ge ($z>0$) having plasma frequency ω_p. We take the surface polaritons to propagate in the y-direction. We assume specular reflection of the electrons in the Ge at the boundary z=0. This is equivalent to evaluating the field in the semi-infinite Ge substrate by assuming mirror image boundary conditions, $E_z(0^+) = -E_z(0^-)$ and $E_y'(0^+) = -E_y'(0^-)$, for an infinite Ge sample. Application of the boundary conditions leads to the dispersion relation for surface polaritons
$$\sum_{\sigma=\pm 1} \sigma\left(1+\frac{\sigma\gamma\alpha_2\epsilon_1}{\alpha_1\epsilon_2}\right)\left(1+\frac{\sigma\alpha_o\epsilon_1}{\alpha_1}\right)e^{\sigma\alpha_1 d} = 0 \qquad (8)$$
where the subscripts 0,1,2 refer to vacuum, GaAs, and n-Ge, respectively, the ϵ_i are the dielectric constants, the $\alpha_i=[q_y^2-(\omega^2/c^2)\epsilon_i]^{\frac{1}{2}}$ are the decay constants of the surface polariton in the respective media, $\gamma = 1-(q_y^2\,\omega_p^2/\,\omega^2\alpha_2\varkappa)$, and $\varkappa = [q_y^2+\beta^{-2}(\omega_p^2-\omega^2)]^{\frac{1}{2}}$. The quantities ϵ_i are given by $\epsilon_1(\omega)=\epsilon_1(\infty)[(\omega_L^2-\omega^2)/(\omega_T^2-\omega^2)]$ and $\epsilon_2(\omega)=\epsilon_2(\infty)[1-(\omega_p^2/\omega^2)]$ where ω_L and ω_T are the long wavelength longitudinal and transverse optical phonon frequencies, respectively of GaAs.

For the case of a slab of n-Ge sandwiched between vacuum and intrinsic GaAs, the field in the slab is evaluated by using mirror image boundary conditions at both boundaries, $z=0$ and $z=-d$. This means, however, that mirror images of the boundaries at $z=0$ and $z=-d$ must also be placed at $z=\pm 2d$, $\pm 4d$, ..., and at $z=+d$, $\pm 3d$, ..., respectively. The dispersion relation is found to be

$$\left(g_2 - \frac{ic\alpha_o}{\omega}\right)\left(g_2 - \frac{ic\alpha_1}{\omega\epsilon_1}\right) = g_1^2 \tag{9}$$

where

$$g_i = -\frac{i\omega d}{\pi^2 c}\left\{\left(\frac{d\alpha_2}{\pi}\right)^2 T_i\left(\frac{dq_y}{\pi},\frac{d\alpha_2}{\pi}\right) - \left(\frac{d}{\pi}\right)^2 BT_i\left(\frac{dq_y}{\pi},\frac{dx}{\pi}\right) - AS_i\left(\frac{dq_y}{\pi}\right)\right\}, \tag{10}$$

$$T_i(x,y) = (y^2-x^2)^{-1}[S_i(x) - S_i(y)], \tag{11}$$

$$S_1(x) = (\pi/x)\operatorname{cosech}\pi x, \quad S_2(x) = (\pi/x)\coth\pi x. \tag{12}$$

3. Results

Numerical calculations have been carried out for a slab of intrinsic GaAs sandwiched between vacuum and n-Ge for several slab thicknesses and carrier concentrations in the Ge. The values of the parameters used were $\omega_L = 290.5\text{cm}^{-1}$, $\omega_T = 268.2\text{ cm}^{-1}$, $\epsilon_1(\infty) = 10.89$, $\epsilon_2(\infty) = 15.13$, and $(m^*/m) = 0.2$. The results for $d = 0.1\ \mu m$ and $100\ \mu m$ and $\omega_p = 400\text{ cm}^{-1}$ are presented in Fig. 1. Three surface polariton modes are found in each case, the upper and lower modes corresponding to interface modes localized at the GaAs-Ge boundary and the middle mode corresponding to the surface mode at the GaAs-vacuum boundary. From the figure, we see that the non-local effects appear only at large wave vectors. Note the termination of two of the modes at small wave vectors. In Fig. 2 we present results for a Ge slab between vacuum and intrinsic GaAs with the same ω_p value and slab thicknesses as in Fig. 1. Again, we have three surface polariton modes in each case. The upper mode terminates at a minimum wave vector. In contrast to the GaAs slab, we now have two modes whose frequency increases strongly at large wave vector.

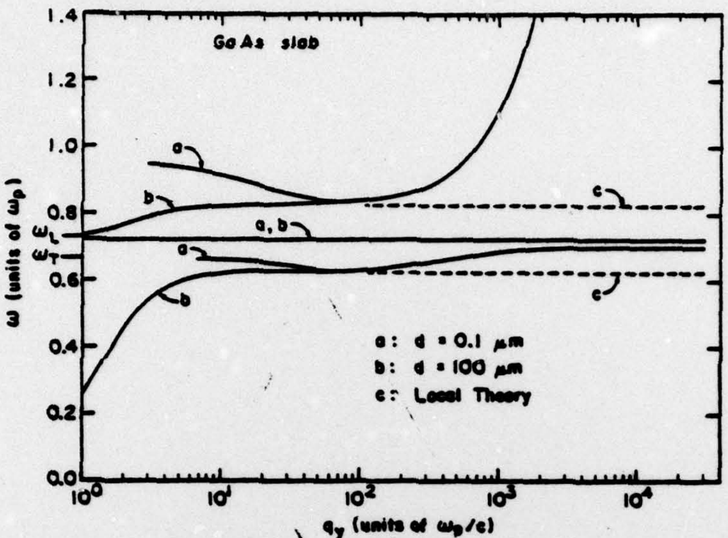

Fig. 1. Surface polariton dispersion curves for an intrinsic GaAs slab between vacuum and n-Ge

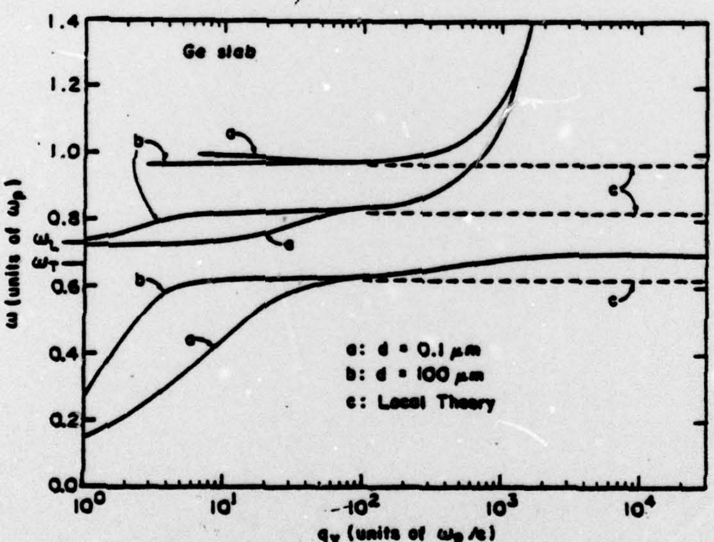

Fig. 2 Surface polariton dispersion curves for an n-Ge slab between vacuum and intrinsic GaAs.

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